

High Energy Neutrino Astrophysics

Teresa Montaruli^a

^aUniversità di Bari and INFN, Via Amendola, 173, I-70126, Bari, Italy, montaruli@ba.infn.it

Astroparticle physics is a field rich of perspectives in investigating the ultra-high energy region which will never be accessible to man made machines. Many efforts are underway in order to detect the first cosmic neutrinos, messengers of the unobserved universe. The motivations of this field of research, the current and next future experimental status are reviewed.

1. Introduction

The observation of neutrinos is an experimental challenge due to their weak interactions that makes them elusive particles. Though they are difficult to detect, they are excellent probes to observe the most distant sources and their interior. Until now only MeV extra-terrestrial neutrinos have been observed from the Sun and SN1987A. Nevertheless there is growing activity to build detectors for high energy ($\gtrsim 1$ TeV) neutrinos of astrophysical origin: their detection would allow the observation of the horizon not accessible to the well-established γ -astronomy.

In Sec. 2 the scientific objectives of ν astrophysics and the connection to the observation of Ultra-High Energy Cosmic Rays (UHECRs) are introduced. The complementarity between γ and ν -astrophysics is pointed out and typical models for ν production are considered. The working principle of Neutrino Telescopes (NTs) exploiting the Cherenkov light detection in the South Pole ice or in sea/lake depths is summarized in Sec. 3. Detector performances, event topologies and background rejection methods are considered. In Sec. 4 the current status of Cherenkov NTs is reviewed, while in Sec. 5 other techniques are considered.

2. Scientific Motivations of ν Astrophysics

Cosmic rays have been observed in huge Extensive Air Shower (EAS) arrays up to energies in excess of 10^{20} eV, exceeding those of any foreseen accelerator machine. The spectrum is im-

pressively regular: 2 power laws with a mass-dependent break at ~ 3000 TeV (the 'knee') beyond which the spectrum becomes softer. It is commonly believed that up to the knee galactic supernovae (SNs) can be the sources of CRs, since they have the proper power to accelerate CRs and to balance the energy density of CRs confined in the Galaxy. Moreover diffusive shock acceleration naturally leads to power law spectra. Most experiments agree that above the knee the composition becomes heavier since the proton gyro-radius in the galactic magnetic fields is smaller than that of Fe nuclei. Another feature at $\sim 10^{19}$ eV (the 'ankle') indicates another possible spectral slope change not yet well established due to the small statistics (~ 1 particle/km²/yr). At these energies the Larmor radius of protons is comparable to the Galaxy size and the ankle could be due to the onset of an extra-galactic component. Most of the EAS observations agree on a proton dominated composition. Nevertheless it is still not possible to establish the fall-off of the CR spectrum above $10^{19.5}$ eV (GZK cut-off), due to p interactions with the Cosmic Microwave Background Radiation (CMBR), since statistics is small and systematic errors large.

Since γ -rays are reprocessed in sources and absorbed by extra-galactic backgrounds (IR, CMB and Radio photons) through pair production, at few hundreds of TeV they do not survive the journey from the Galactic Center. Protons cannot access regions at distances $\gtrsim 50$ Mpc at energies $E > 50$ EeV at which they are deflected by $< 1^\circ$ by magnetic fields. Neutrons of EeV energies have decay lengths of the order of 10 kpc. Hence, there

is no doubt that neutrinos, and possibly gravitational waves, propagating almost undisturbed by encountered matter and magnetic fields, represent the 'probes' of the Universe with unique discovery potentials. They could allow us to answer the question: '*Which are the sources of the highest energy cosmic rays?*'. Review papers on ν astrophysics are in [1].

Models for high energy CR production and acceleration are divided into 2 classes: top-down models, that imply super-massive relic decays, and bottom-up models. In bottom-up scenarios protons or nuclei are accelerated and interact with matter or photons surrounding the accelerator, hence producing mesons. Neutral pions decay into γ s and from charged pion decay (if all μ 's decay too) the ν species are produced in a flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, since ν_τ production at source from charmed mesons is negligible. Moreover after propagation through cosmological distances, these ratios are altered by $\nu_\mu \rightarrow \nu_\tau$ oscillations into $1 : 1 : 1$ (even though other scenarios involving ν decay are possible). From these reactions the strict relationship between gamma and neutrino astrophysics emerges. It is reasonable to assume that at the sources photon and neutrino spectra have similar shape and normalization (even if absorption effects can be not negligible), typically $\frac{dN}{dE} \propto E^{-(2 \div 2.5)}$, as expected from 1st order Fermi acceleration mechanism. Irrespective of details of acceleration mechanisms, the maximum energy of CRs accelerated in a site of dimensions R in the presence of magnetic fields B can be calculated considering that the Larmor radius of particles cannot exceed R . It results in $E_{\max} \sim \beta Z \left(\frac{B}{1 \mu\text{G}} \right) \left(\frac{R}{1 \text{kpc}} \right) 10^{18} \text{ eV}$, where β is the velocity of a shock wave in units of velocity of light or the efficiency of the acceleration mechanism. Other ν production mechanisms are photopion production due to UHECR interactions with the CMBR ('GZK ν 's') [2] and Z decays due to UHE ν 's interacting on cosmic background ν 's [3].

Examples of sources accelerating CRs up to energies of 10^{19} eV are extra-galactic sources, such as inflows onto super-massive black holes at centers of Active Galactic Nuclei (AGNs) and Gamma-Ray bursters (GRBs). If the sources of

the observed highest energy CRs are optically thin to proton photo-meson and proton-nucleon interactions, so that protons escape, an upper limit to the ν flux (hereafter W&B limit) can be calculated [4]. This flux corresponds to $\sim 200 \text{ events/km}^2/\text{yr}$. It should be considered that the W&B flux is derived normalizing the observed proton flux at 10 EeV and extrapolating it at lower energies using an E^{-2} source spectrum. It can be evaded considering other spectral dependences; moreover magnetic field effects and uncertainties in photohadronic interactions can reduce the number of protons able to escape, hence affecting the limit [5]. Galactic sources are not subject to these limits due to their proximity. Possible sources of HE ν 's are micro-quasars, exploding stars and consequent neutron stars in SNRs, magnetars and the rates vary from fractions of events up to hundreds in km^2 detectors.

There is not a convincing evidence nowadays on the existence of hadronic acceleration in sources. The TeV gamma sky is of great interest for ν astrophysics since if a strong indication emerges that γ s are not produced by electromagnetic processes but in π^0 decay, HE ν 's should be produced as well by charged π s. Current TeV catalogues include about 20 sources detected by imaging atmospheric Cherenkov (IAC) detectors, mainly extra-galactic BL Lacs and galactic SN remnants (SNR). CANGAROO IAC experiment has detected at $\sim 7\sigma$ level TeV emissions from the Galactic Center [6], and it is expected to be confirmed by HESS soon. The claim by CANGAROO [7] on the better compatibility of TeV γ -ray measurements from the SNR RX J1713.7-3946 with a π^0 decay hypothesis compared to electromagnetic mechanisms (bremsstrahlung and inverse Compton) is still controversial [8]. There is room for a π^0 decay contribution in HE tails of multi-wavelength spectra of some TeV sources, such as the Crab, PSR 1706-44, Cas A, plerions and shell-type SNRs.

3. Cherenkov Neutrino Telescopes

Neutrinos can be detected through their charged current (CC) interactions in 3-D arrays of optical modules (OMs), pressure resistant glass

spheres containing phototubes (PMTs), located in polar ice or sea/lake water. OMs distances are optimized considering light transmission properties and construction constraints. The time and position of PMTs hit by Cherenkov light emitted by relativistic particles allow the reconstruction of tracks. Charge amplitudes are used to measure μ and shower energies. The selection of detector sites is determined by transmission light properties, environmental backgrounds, stability of media properties in the implemented region, mechanical, construction and infrastructure constraints. In Sec. 4 merits and drawbacks of ice and water properties are discussed.

For various reasons this technique improves with energy. ν cross-sections and μ range increase with energy, and hence the effective target mass. The amount of light also increases hence reconstruction of μ tracks and of cascades induced by $\nu_{e,\tau}$ and NC can improve. Moreover the signal to noise ratio (S/N) improves with energy, since the atmospheric μ and ν fluxes are steeper ($\sim E^{-3.6}$ for $E \gtrsim 100$ GeV) than fluxes expected from sources ($\sim E^{-2}$).

In order to reduce the μ flux by orders of magnitude, detectors are located below kms of matter, underwater or underice. The rejection of atmospheric μ 's is achieved looking at events from the lower hemisphere, induced by ν 's crossing the Earth, or using HE cuts in case also events from above should be recovered from the background. In fact, at ~ 40 TeV the ν_μ interaction length equals the Earth diameter and at $E \gtrsim 1$ PeV ν_μ absorption is severe. On the other hand, the Earth is transparent to ν_τ thanks to τ decay producing another ν_τ . Hence NTs need to have good shower, track reconstruction capabilities and energy resolution.

The atmospheric ν background rejection in astrophysical ν searches depends on strategies. For point-like sources, statistically significant clusters of events with respect to the atmospheric ν distributions are looked for. Methods are based on angular cuts optimized in order to have the best S/N ratios in case of binned methods or on the measurement of the energy dependent point-spread function for unbinned methods. As a matter of fact, the distribution of events around the point

source is different from the background. In case of time-dependent emissions, such as GRBs, further time requirements strongly reduce the backgrounds. It is clear that a relevant parameter for point-like source searches is the angular resolution. For galactic sources, for which typically ν emissions do not exceed energies much larger than 100 TeV, a good angular resolution provides a substantial mean to reject the backgrounds. On the other hand, for diffuse extra-galactic sources the S/N ratio is optimized using minimum energy cuts and exploiting the different energy dependence of signal and noise spectra. Both μ tracks or cascades are used for diffuse flux searches. Typically, the direction of ν parents of cascades is detected with worse resolution than for μ 's (typically $\lesssim 30^\circ$ above 10 TeV), while the energy resolution is competitive (for μ 's $\sim 30 - 40\%$ in $\log E$, for showers $\sim 20\%$ in E above 10 TeV).

The effective area for ν 's, that is the sensitive area 'seen' by ν 's producing detectable μ 's when entering the Earth, is a useful parameter to determine event rates and to be compared between experiments. In fact, the event rate for a ν model predicting a spectrum $\frac{d\Phi}{dE_\nu d\Omega_\nu}$ is given by $N_\mu = \int \int dE_\nu d\Omega_\nu A_\nu^{eff}(E_\nu, \Omega_\nu) \frac{d\Phi}{dE_\nu d\Omega_\nu}$. It depends on track reconstruction quality cuts and selection criteria for background rejection, on the μ range, ν cross section and on the ν absorption in the Earth. Being strongly energy dependent, the mean energy of atmospheric ν 's producing detectable events is ~ 100 GeV, while for an E^{-2} spectrum it is ~ 10 TeV.

4. Experimental Status and Results

The NT currently taking data are AMANDA at the South Pole [9] and NT200 (192 OMs on 8 strings) in Lake Baikal (Siberia) [10] at 1.1. km depth. Baikal effective area for μ 's is 2000 m² at 1 TeV and the sensitivity to cascades is competitive to AMANDA. By implementing 3 additional strings carrying only 6 couples of OMs vertically spaced by 70 m, at a distance of 100 m from the detector centre (of diameter of 43 m) the sensitivity to cascades will improve by a factor of 4. Baikal was the first underwater telescope to reconstruct atmospheric ν 's in 1996.

AMANDA is running now in the AMANDA-II configuration with 677 OMs with 8-inch PMTs on 19 strings implemented between 1.5-2 km deep in the ice. The angular resolution for μ tracks has improved from $\sim 4^\circ$ for the previous configuration AMANDA-B10 [11] (302 OMs on 10 strings) to $2 - 2.5^\circ$. The effective area for μ 's, that has largely improved in the horizontal direction, is $\sim 0.02 - 0.04 \text{ km}^2$ for an E^{-2} ν flux depending on the source declination. From the two 'calibration' test beams of atmospheric μ 's and ν 's a systematic error of 25% on detector acceptance is derived mainly due to OM sensitivity and ice optical property knowledge. The upper limits for μ fluxes for point sources calculated using 699 upward events selected in 197 d during the year 2000, are shown in Fig. 1. The most significant excess, observed around 21.1h R.A. and 68° declination, is of 8 events and the expected background is 2.1. The probability to observe such an excess as a random fluctuation of the background is 51%. Limits from other experiments of smaller area ($\sim 1000 \text{ m}^2$), Super-Kamiokande (SK)[12] and MACRO [13] in the upper hemisphere, are reported. It is interesting to notice that the MACRO scintillator+tracking detector, with angular resolution $\lesssim 1^\circ$, in a sample of 1388 upward-going μ 's has found an excess in the Circinus Constellation region. Ten events have been detected inside a 3° half-width cone (including 90% of an E^{-2} signal) around the plerion PSR B1509-58 and 2 are expected from atmospheric ν 's. This source was also detected by CANGAROO in 1997 above 1.9 TeV with 4σ significance, but not confirmed by 1996 and 1998 data with 2.5 TeV threshold [14]. Even though PSR B1509-58 is of interest as possible ν emitter, the significance of MACRO result is negligible when all the 1388 directions of the measured events are looked at. Moreover, it is expected that $E^{-(2 \div 2.5)}$ signals should produce at least 4-7 events in 1.5° around the source while only 1 is detected and the expected background is 0.5. From the same sources SK observes the largest number of events between the selected catalogue looked at, but the data are still compatible with background fluctuations (9 events to be compared to a background of 5.4). The sensitivity of ANTARES (expected

angular resolution of $\sim 0.2^\circ$ for $E_\nu > 10 \text{ TeV}$) is also shown for 1 yr of data taking [15].

Upper limits for E^{-2} diffuse fluxes of $\nu_\mu + \bar{\nu}_\mu$ are summarized in Tab. 1. When specific spectral shapes of models are considered, it results that some ν models from AGNs/blazars and quasars are excluded by the AMANDA B-10 limit, while this is still higher than the W&B limit of $4.5 \cdot 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. Upper limits on diffuse fluxes of cascades induced by all flavor ν 's are shown in Fig. 2.

ANTARES [15] will be located in front of Toulon, South France, 40 km off-shore at a depth of 2400 m. It will consist of 12 strings carrying 75 OMs each, containing 10-inch PMTs. The electro-optical cable (EOC) already connects since Dec. 2002 the shore station to the junction box, that distributes data and power to strings. Submarine connections were successful in Mar. 2003 when a prototype (1/5 of a string with 15 OMs), was deployed together with an instrumentation string for environmental parameter measurements. The detector is expected to be completed by the end of 2006.

NESTOR [16] is aiming at the construction of a NT close to Pylos (Greece) at $\sim 4 \text{ km}$ depth. Proposed towers are made of 12 hexagonal floors of 32 m diameter spaced by 30 m each carrying 6 upward-looking and 6 down-ward looking OMs with 15-inch PMTs. The effective area for $E_\mu > 10 \text{ TeV}$ is $\sim 0.02 \text{ km}^2$. In Mar. 2003 a prototype 12 m diameter floor was deployed and PMT data were transmitted to shore through a 35-km EOC.

In the next future the community is aiming at the construction of detectors at the scale of km^3 . The IceCube project [17] is already funded and detector construction will start in the Austral summer of 2004-5 and will continue for about 6 years. It will consist of 4800 DOMs (digital OMs) on 80 strings each with 60 10-inch PMTs vertically spaced by 17 m extending from 2.4 km up to 1.4 km depths. The strings are at vertices of equilateral triangles with 125 m long side. Close to each string hole there will be 2 iced water tanks seen by 2 DOMs, forming the IceTop array for CR composition measurements and absolute pointing determination. The μ declared effective area after selection requirements is $> 1 \text{ km}^2$ above 10 TeV,

Table 1

90% upper limits on μ fluxes above $E_{\mu \min}$ and to diffuse $\nu_{\mu} + \bar{\nu}_{\mu}$ E^{-2} fluxes in the given energy intervals. For ANTARES (error due to prompt ν prediction uncertainties) and IceCube the expected sensitivities are given. μ track reconstruction is required (except for the UHE limit by AMANDA B-10 for showering μ 's obtained using neural network methods) and energy cuts are used to reject atmospheric backgrounds.

Experiment	Run time	Energy	Φ_{μ}	Φ_{ν}
Reference	(yrs)	range	$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$	$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$
AMANDAB-10[19]	0.36	$E_{\nu} \sim 6 - 10^3 \text{ TeV}$		$8.4 \cdot 10^{-7}$
AMANDAB-10 [20]	0.36	$E_{\nu} \sim 2.5 - 5.6 \cdot 10^3 \text{ PeV}$		$7.2 \cdot 10^{-7}$
MACRO [21]	5.8	$E_{\nu}(E_{\mu \min}) \sim 10^4 - 10^6 (1.5) \text{ GeV}$	$1.7 \pm 0.2 \cdot 10^{-14}$	$4.1 \pm 0.4 \cdot 10^{-6}$
Soudan2 [22]	6.34	$E_{\mu \min} \sim 5 - 20 - 100 \text{ TeV}$	$2.2 - 1.5 - 1.4 \cdot 10^{-14}$	
Frejus [23]	3.27	$E_{\nu} \sim 2.6 \text{ TeV}$		$4.7 \cdot 10^{-6}$
ANTARES [15]	3	$E_{\mu \min} = 125 \text{ TeV}$		$3.9 \pm 0.7 \cdot 10^{-8}$
IceCube [17]	3	$E_{\nu} \gtrsim 100 \text{ TeV}$		$4.2 \cdot 10^{-9}$

the angular resolution is expected to be $< 1^\circ$ at high energies, the energy resolution $\sim 30\%$ in $\log E_{\mu}$ and $\sim 20\%$ in E for cascades.

In order to cover the entire sky, particularly the region of the Galactic Center, a km^3 detector is envisaged also in the Mediterranean. Being located in sea water, it will provide complementarity respect to IceCube for what concerns media properties and environmental backgrounds. Media transmission properties are characterized by the attenuation length, the sum of the absorption and scattering lengths. Absorption reduces signal amplitudes, hence it mainly affects the choice of the distance between OMs. Scattering length affects the direction of light propagation and the arrival time of photons on OMs, hence the angular resolution. A useful parameter is the effective scattering length which takes into account the angular distribution of scattered photons. It was found by the AMANDA experiment that ice properties depend on depth: the presence of air bubbles in the ice is much reduced below depths of 1 km, and at the depths in which AMANDA is currently located (1.5-2 km) the scattering is $\lambda^{eff} \sim 25 \text{ m}$, even though the ice property dependence on depth and the effect of bubbles that form around OMs after drilling, is still one of the main sources of uncertainty. In comparison, in sea and lake water $\lambda^{eff} > 100 - 200 \text{ m}$.

The Italian NEMO project [18] for a $\text{km}^3 \nu$ tele-

scope has started in 1998 an R&D activity on the selection of the optimal site through more than 20 sea campaigns, on electronics and materials suitable for long-term undersea measurements, on large area photo-sensors. More recently the realization of an underwater laboratory (Phase 1 test site) close to Catania connected to shore by an 28 km-long EOC, where a couple of prototype towers will be deployed, has been funded. Performance studies have produced a modular detector concept made of towers $\sim 600 - 700 \text{ m}$ high at distances $\gtrsim 120 \text{ m}$. Configurations with ~ 5000 OMs should achieve at $E_{\mu} > 100 \text{ TeV}$ effective areas $> 1 \text{ km}^2$ and angular resolutions $< 0.1^\circ$. The selected optimal site is Capo Passero, 80 km off-shore Catania, 3400 m deep. NEMO performed comparative sea campaigns in collaboration with ANTARES and Baikal [18]. From these campaigns values of the absorption length of 48 and 66 m for ANTARES and Capo Passero sites, respectively, at around 450 nm, have been measured and values of 15-30 m in Lake Baikal, while typical values in ice are $\gtrsim 100 \text{ m}$.

Concerning environmental backgrounds, in sea water continuous rates of the order of tens of kHz are observed due to ^{40}K decay and bursts up to several tens of MHz due to living organisms. In ice these backgrounds are not present, while small contributions at kHz level are due to OM materials. The longest term measurement ($\sim 100 \text{ d}$) of

optical background was performed by ANTARES using the already mentioned prototype string. Counting rates show large and short lived peaks due to bioluminescence, over a continuous baseline rate of ~ 60 kHz due to ^{40}K and bacteria, that varies up to 250 kHz. Studies on correlations between bioluminescence, sea currents and string movements are underway. At Capo Passero, the NEMO collaboration measured an average rate of 28.5 kHz in 4 days at a threshold of 0.35 photoelectrons, while the same device measured 58 kHz at ANTARES site in 4 days. Using the 12 PMT floor, NESTOR found that bioluminescence contributes to the triggered event sample by $\sim 1\%$ of the experiment active time and with 4-fold coincidence requirements the trigger rate is 2.6 Hz (30 mV threshold). Sedimentation and fouling of optical surfaces causing a glass transparency reduction of OM surfaces ($< 2\%$ in 1 yr and saturates) have been measured by ANTARES between July-Dec. 97: the sediment flux varies between $100\text{--}350 \text{ mg m}^{-2} \text{ d}^{-1}$, respectively in summer and autumn due to clays dragged by rivers. The measured flux at Capo Passero is $20 \text{ mg m}^{-2} \text{ d}^{-1}$ on average in 40 d, but longer term measurements are underway.

5. Other Techniques

Electro-magnetic cascades induced by $\nu_{e,\tau}$ in dense media produce coherent radio pulses of Cherenkov radiation of few ns duration (Askaryan effect [25]) with power concentrated around Cherenkov angle. The RICE detector [26] exploits this technique using 16 radio-receivers at 100-300 m in AMANDA holes with an effective bandpass of 200-500 MHz and an attenuation length in ice of > 1 km. Such a cheap technique has produced limits competitive to AMANDA ones, even though further investigations on backgrounds is ongoing. This technique is used also for cascades induced in the lunar regolith and in salt domes. Another technique exploits acoustic detection of bipolar pulses of $\sim 10 \mu\text{s}$ duration caused by expansion of homogeneous media due to energy deposited by showers that converts into heat. At typical frequencies of 10 kHz, sound waves propagate kms in water. Limiting factors

are the high directionality of the acoustic pattern, that restricts the solid angle accessible to sensors, and the noise due to mammals, wind, thermal noise and human factors. Currently an acoustic military array close to Bahamas is studying these aspects [27]. Most of the Cherenkov NTs also plan to deploy hydrophones. For instance NEMO is going to deploy 4 hydrophones at the test site. Finally, methods suitable for ν_τ detection with fluorescence and Cherenkov arrays have been proposed, such as detection of showers induced by τ leptons emerging from mountains or Earth-skimming upward τ 's decaying after crossing ~ 10 kms along Earth cords [28].

These techniques have larger energy thresholds ($\sim 10^{18}$ eV) than Cherenkov NTs, hence cannot take profit of the atmospheric ν measurement for 'calibration' purposes.

6. Conclusions

The current status of NTs has been summarized. No positive signal has been observed up to now. The construction of km^3 arrays with the proper discovery potentials is a challenge that is going to start very soon.

Acknowledgments

I would like to thank the organizers of the conference, particularly W.C. Haxton, and F. Halzen, S. Cecchini and F. Arneodo.

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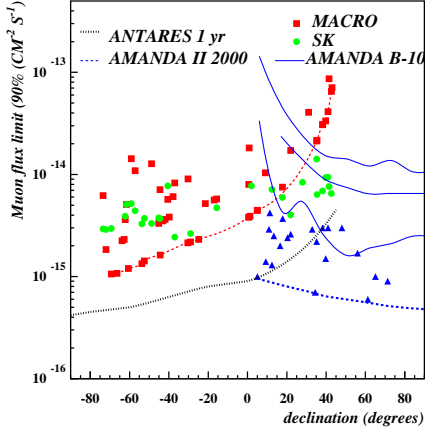


Figure 1. 90% c.l. upper limits on μ fluxes induced by ν 's with E^{-2} spectrum vs source declination for SK (green circles) [12], MACRO (red squares) (updated with respect to [13]), AMANDA-B10 [11], AMANDA-II 2000 data (triangles), ANTARES sensitivity (dotted black line) after 1 yr [15]. It has not been possible to apply a correction due to different μ average energy thresholds (SK ~ 3 GeV, MACRO ~ 1.5 GeV, AMANDA ~ 50 GeV). Nevertheless, the maximum of the response curves of these detectors for an E^{-2} flux is at $E_\mu \sim 10$ TeV, hence events contributing between 1-50 GeV should not make a large correction to these limits.

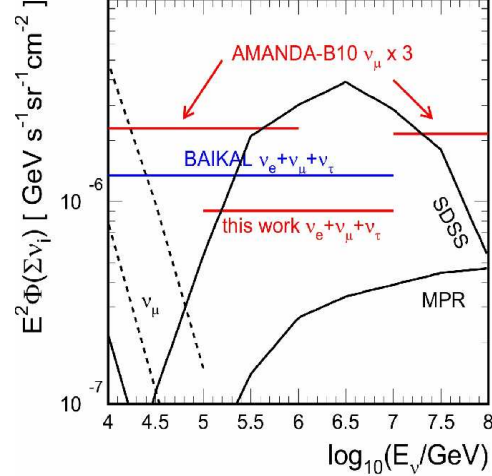


Figure 2. 90% c.l. upper limits on diffuse $E^{-2} \nu$ flux for cascades of all flavors. The AMANDA-II (197 d) [24] and Baikal (268 d) [10] results are presented compared to atmospheric ν fluxes, an AGN model (SDSS) and an upper limit on ν fluxes [5]). For comparison the AMANDA B-10 ν_μ limits are shown multiplied by a factor of 3 (the underlying hypothesis is that at source the proportion between flavors is $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, while at Earth, due to oscillations, it is $1 : 1 : 1$).

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